

SOYBEAN

Deep and Shallow Fall Tillage for Irrigated Soybean Grown with Different Weed Management Systems in the Midsouthern USA

Larry G. Heatherly,* Stan R. Spurlock, and C. Dennis Elmore

ABSTRACT

Management inputs that maximize economic return from early soybean [*Glycine max* (L.) Merr.] production system (ESPS) plantings in the midsouthern USA have not been evaluated fully. The objective was to determine the effect of different weed management systems on yield and net return from irrigated ESPS plantings of soybean following deep (DT; 40–45 cm deep) and shallow (ST; <10 cm deep) fall tillage. Adjacent experiments receiving either DT or ST were conducted in 1999 and 2000 on Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquert) near Stoneville, MS (33°26' N lat). Weed management systems were (i) glyphosate-resistant (GR) cultivar with pre-emergent (PRE) nonglyphosate [N-(phosphonomethyl)glycine] herbicides followed by one postemergent (POST) application of glyphosate timed to control grasses, (ii) GR cultivar with two POST applications of glyphosate timed to control both grasses and broadleaves, (iii) GR cultivar with PRE nonglyphosate herbicides followed by two POST applications of glyphosate timed to control both grasses and broadleaves, (iv) non-GR cultivar with PRE herbicides followed by one POST application of a grass herbicide, (v) non-GR cultivar with POST application of herbicides timed to control both grasses and broadleaves, and (vi) non-GR cultivar with PRE herbicides followed by POST applications of herbicides timed to control both grasses and broadleaves. Fall DT was more expensive than ST but resulted in taller soybean plants and less weed cover at harvest. Average yields and net returns from DT and ST were 4286 and 4085 kg ha⁻¹ and \$364 and \$362 ha⁻¹, respectively. Thus, the investment in equipment for fall DT for irrigated ESPS plantings is not justified. Postemergent-only weed management was the cheapest for both GR and non-GR cultivars. Weed management that used POST-only glyphosate resulted in the greatest yield and profit from GR cultivars. With non-GR cultivars, yields were not affected by weed management, but net returns were lower when the most intensive weed management was practiced.

THE ESPS (planting soybean in late March through late April compared with planting in early May and later) produces maximum yields in both nonirrigated and irrigated environments in the midsouthern USA (Heatherly, 1999a; Heatherly and Spurlock, 1999). Deep tillage (subsoiling) has enhanced dryland yields of both ESPS and later soybean plantings on some clay soils in the midsouthern USA (Wesley and Smith, 1991; Wesley et al., 1994, 2001; Heatherly and Spurlock, 2001; Popp

et al., 2001; Heatherly et al., 2002) and on coastal plain soils in the southeastern USA (Frederick et al., 1998).

Deep tillage is used to disrupt the soil profile below 15 cm (Hoeft et al., 2000). Shallow tillage refers to operations that affect soil to depths up to 15 cm. In nonirrigated studies where all tillage was performed in the late winter or early spring on Sharkey clay soil where the profile was wet beneath the dry surface, Heatherly (1981) measured soybean yields that were similar following either DT or following shallow, disk-harrow tillage. Popp et al. (2001) found that DT of wet clay soil in late winter or early spring in Arkansas resulted in net returns from nonirrigated soybean that were similar to those resulting from conventional ST. Thus, DT of wet clay soils in late winter or early spring was not effective in increasing net return.

In contrast to winter/spring DT of wet clay soils, later studies were conducted where DT was performed in the fall when the profile was dry. Wesley and Smith (1991) measured significant yield increases from nonirrigated May plantings following fall DT of a dry Tunica silty clay soil (clayey over loamy, smectitic, nonacid, thermic, Vertic Haplaquept) in Mississippi in years when drought occurred during the growing season. Wesley et al. (2000) determined that net return was greatly increased from this practice. The increased production was associated with increased moisture content in the soil, presumably because of greater infiltration and storage of winter rain resulting from fall DT. This work has been used to promote DT of dry clay soils in the fall in the midsouthern USA for nonirrigated soybean production.

Studies on Sharkey clay in Arkansas (Popp et al., 2001) and Mississippi (Wesley et al., 2001) showed average yield increases of 580 and 365 kg ha⁻¹, respectively, and average increases in net return of \$96 and \$71 ha⁻¹, respectively, from fall DT preceding nonirrigated soybean production. In the Arkansas study, yields following fall DT were significantly greater than those from conventional tillage even though drought was not severe. The Mississippi study used estimated DT costs that were \$17 to \$20 ha⁻¹ more than those for a treatment that received only ST (≤10 cm). Heatherly and Spurlock (2001) and Heatherly et al. (2002) determined that net returns from producing nonirrigated soybean following DT of Sharkey clay were significantly greater than those from conventional tillage only when plantings were made in April vs. May and later. In their study, costs

L.G. Heatherly, USDA-ARS, Crop Genet. and Prod. Res. Unit, P.O. Box 343, Stoneville, MS 38776; S.R. Spurlock, Dep. of Agric. Econ., P.O. Box 9755, Mississippi State, MS 39762; and C.D. Elmore, USDA-ARS Application and Prod. Technol. Res. Unit, P.O. Box 36, Stoneville, MS 38776. Received 24 June 2003. *Corresponding author (lheatherly@ars.usda.gov).

Published in Agron. J. 96:734–741 (2004).
© American Society of Agronomy
677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DT, deep tillage; ESPS, early soybean production system; GR, glyphosate resistant; POST, postemergent; PRE, pre-emergent; ST, shallow tillage; WMS, weed management system.

associated with DT were \$29 to \$42 ha⁻¹ greater than those for a conventional ST system (fall tillage with a disk harrow and/or a spring-tooth harrow) because of expense associated with DT and one extra ST operation to smooth the soil surface following DT. In extremely dry years (yield levels < 1000 kg ha⁻¹), DT provided no yield or economic benefit (Heatherly et al., 2002). On a coastal plain loamy sand soil in South Carolina, Frederick et al. (2001) measured a 12% yield increase from DT compared with no DT (2415 vs. 2160 kg ha⁻¹) just before May planting of soybean that was not irrigated.

In irrigated soybean production systems on the sandy soils of the southeastern USA, DT provided no yield or economic benefit (Camp and Sadler, 2002; Frederick et al., 2001). Yields following irrigation without DT greatly exceeded yields following DT and no irrigation. Unlike irrigation, use of DT will not guarantee alleviation of water-deficit stress, especially when plantings are made in May and later (Heatherly and Spurlock, 2001; Camp and Sadler, 2002; Heatherly et al., 2002). Therefore, in situations where irrigation is available and economical, DT may not be profitable. The economic feasibility of replacing DT with irrigation in areas where summer rainfall is deficient should be considered.

Tillage system not only can affect growth of nonirrigated soybean in ESPS plantings on clay soil in the midsouthern USA (Heatherly and Spurlock, 2001), but also weed management. Koskinen and McWhorter (1986) predicted increased populations of perennial and biennial weeds from using reduced-tillage systems; thus, DT of clay soils could be considered for suppressing problem perennial weeds such as redvine (*Brunnichia ovata* Walt.) and johnsongrass [*Sorghum halepense* (L.) Pers.]. These tillage-related weed management concerns may entail adopting different weed control strategies for different tillage management systems used for soybean in the midsouthern USA.

Many weed management systems (WMSs) provide similar control levels, but cost differences can be large. Cost difference, coupled with yield differences among WMSs, can mean significant differences in net return among weed control systems (Poston et al., 1992; Heatherly et al., 1993, 1994; Buhler et al., 1997; Johnson et al., 1997; Nelson and Renner, 1999; Webster et al., 1999; Reddy and Whiting, 2000; Reddy, 2001a). Thus, effective weed management programs that are economical for a given production system must be determined to maximize profits.

Traditionally, herbicides were tailored largely for crops rather than crops tailored to tolerate a specific herbicide. During the past decade, advances in biotechnology coupled with plant breeding have resulted in the development of herbicide-resistant soybean cultivars. As of 2000, GR soybean represents all of the hectareage planted to transgenic soybean (Reddy, 2001b). Well over half of the U.S. soybean area is planted to GR soybean cultivars, with some states having more than two-thirds of their soybean area in GR soybean. Reddy et al. (1999) and Reddy (2001b) recently summarized

the current situation pertaining to the use of GR soybean cultivars.

Glyphosate-resistant cultivars offer producers the flexibility to control a broad spectrum of weeds in soybean without crop safety concerns (Reddy, 2001b). Weed control cost is less, even when the higher cost for seed of most GR cultivars is considered (Reddy et al., 1999; Roberts et al., 1999; Webster et al., 1999; Reddy and Whiting, 2000; Reddy, 2001a). This translates to increased profits if yields from GR cultivars are equal or nearly equal to those from conventional cultivars (Reddy and Whiting, 2000). However, if yields of GR cultivars are greatly below those of conventional cultivars, the cost advantage for a weed management program with glyphosate will not result in greater net returns (Webster et al., 1999).

Research has shown that nonglyphosate PRE herbicides do not adversely affect GR soybean (Gonzini et al., 1999; Nelson and Renner, 1999; Webster et al., 1999; Reddy, 2001a). This means that residual herbicides can be used on plantings of GR cultivars to prevent early-season weed competition in situations where a timely application of glyphosate is not possible (Corrigan and Harvey, 2000). Glyphosate applied at labeled use rates does not affect GR soybean adversely (Nelson and Renner, 1999; Reddy et al., 2000; Elmore et al., 2001). Glyphosate applied alone in a timely manner to GR soybean plantings needs no supplementation with nonglyphosate herbicides to achieve maximum weed control and yield (Gonzini et al., 1999; Webster et al., 1999; Corrigan and Harvey, 2000; Reddy and Whiting, 2000; Reddy, 2001a). All of these advantages should translate to a reduction in management decisions for producers related to weed control in soybean when GR cultivars are used.

Clayey soils occupy more than 3.65 million ha, or about 50% of the land area in the lower Mississippi River alluvial flood plain in the midsouthern USA. Of these soils, Sharkey is the dominant series and comprises about 1.2 million ha in the Mississippi River flood plain regions of Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee (Pettry and Switzer, 1996). The effect of DT on yields from irrigated ESPS plantings has been assumed to be nil, but weather patterns and recent observations in ESPS plantings in the midsouthern USA region justify investigating the validity of this assumption. Weed management strategies using PRE and POST herbicides in irrigated ESPS plantings following fall ST and DT have not been determined. The objective of this work was to compare yields and economic returns from irrigated GR and non-GR soybean grown under WMSs using PRE and POST applications of herbicides in April plantings following fall ST and DT. Economic analysis of 2 yr of results was conducted to assess and compare the profitability of WMSs in the two tillage environments.

MATERIALS AND METHODS

Irrigated field studies were conducted on Sharkey clay soil in 1999 and 2000 near the Delta Research and Extension

Table 1. Average daily maximum air temperatures (max. T) and total rainfall amounts for indicated months in 1999 and 2000, and 30-yr normals at Stoneville, MS.

Month	1999		2000		30-yr normals†	
	Max. T	Rain	Max. T	Rain	Max. T	Rain
	°C	mm	°C	mm	°C	mm
Apr.	25.5	161	22.2	282	23.5	137
May	28.9	144	29.5	176	28.0	127
June	31.7	71	32.2	156	32.0	94
July	33.9	26	34.4	16	33.0	94
Aug.	35.6	6	36.7	0	32.5	58
Sept.	31.7	44	31.1	66	29.5	86

† 1964–1993, Boykin et al. (1995).

Center at Stoneville, MS (33°26' N). Adjacent experiments receiving either fall ST or DT were established and maintained for the duration of the study. Each year's experiment was conducted in a randomized complete block design with four replicates. All experimental units remained in the same location for the duration of the research.

In late September or early October preceding each year's experiment, appropriate areas were either deep-tilled at a 45° angle to the row direction with a chisel plow implement having curved tines spaced 1 m apart or shallow-tilled using a disk harrow and/or spring-tooth cultivator. The DT was done to a depth of approximately 0.4 to 0.45 m. The last irrigation application was made 4 wk or more before DT. Rainfall during the 30 d preceding DT was 74 mm in 1998 and 38 mm in 1999; thus, the soil was relatively dry preceding each year's DT. Shallow tillage (two operations on ST and three on DT) with a disk harrow and/or a spring-tooth cultivator was conducted on both ST and DT after completion of DT operations to prepare a smooth seedbed for the next year's planting. Weather data in Table 1 were collected about 4 km from the experimental site.

Seed of Maturity Group (MG) IV GR ('SG 468' in 1999 and 'SG 498' in 2000) and MG IV non-GR ('AP 4880' in 1999 and 'AP 4882' in 2000) cultivars were planted on 22 Apr. 1999 (day of year 112) and 20 Apr. 2000 (day of year 111). SG 468 and SG 498 are GR half-siblings; AP 4880 and AP 4882 are non-GR half-siblings. Cultivars were chosen because of their consistent high performance on a large hectareage in the region. A plate planter with double-disk openers and closing wheels to seal the seed trench was used. Seed were treated before planting with mefenoxam [(R)-2-[2,6-(dimethylphenyl)-methoxyacetyl-amino]-propionic acid methyl ester] fungicide as a

precaution against *Pythium* spp. Row spacing was 0.5 m, and seeding rate was 16 seed m⁻¹ row, or about 50 kg ha⁻¹ seed. Plots were 25 m long and 4 m (eight rows) wide. Glyphosate was applied to kill existing vegetation before seed being planted into a stale seedbed (not tilled before planting in the spring; Heatherly, 1999c).

Weed management systems were selected along the following premises. First, uncontrolled weeds will reduce soybean yield; therefore, no weedy check was included. The intent in this experiment was to ensure that all WMSs controlled weeds up to the start of irrigation. Second, the inclusion of economic analyses in this study dictated that all WMSs be practical and realistic. Also, there was no intent to determine how WMS related to an economically unattainable or unfeasible weed-free environment. Therefore, a weed-free check was not included. Finally, the intent was to have weed management options that differ in cost. One way of doing this is to use PRE (based on expected weed infestations) vs. POST (based on actual weed infestations) herbicides in various combinations and GR and non-GR cultivars. Based on these premises, WMSs were (i) GR cultivar with PRE nonglyphosate herbicides followed by one POST application of glyphosate timed to control grasses, (ii) GR cultivar with two POST applications of glyphosate timed to control both grasses and broadleaves, (iii) GR cultivar with PRE nonglyphosate herbicides followed by two POST applications of glyphosate timed to control both grasses and broadleaves, (iv) non-GR cultivar with PRE herbicides followed by one POST application of a grass herbicide, (v) non-GR cultivar with POST application of herbicides timed to control both grasses and broadleaves, and (vi) non-GR cultivar with PRE herbicides followed by POST applications of herbicides timed to control both grasses and broadleaves. Weed control measures within each WMS across ST and DT were the same and were applied at the same time across ST and DT within each year.

Within each WMS, use of herbicides and their combinations was dictated by expected weed populations for PRE application or actual populations for POST applications. Selection of POST herbicides was based on assessment of the presence and size of particular weed species in plots of each WMS. Herbicides (Table 2) were broadcast-applied each year at labeled rates with recommended adjuvants and in recommended tank mixes. Pre-emergent herbicides were applied immediately after planting each year. In each year, rainfall of at least 13 mm occurred within 10 d of each PRE application. Pre-emergent herbicides and POST broadleaf herbicides were ap-

Table 2. Pre-emergent (PRE) and postemergent (POST) herbicides applied to weed management systems (WMS) for irrigated glyphosate-resistant (GR) and non-GR soybean grown at Stoneville, MS, 1999–2000.

WMS†	Herbicide‡§
1999	
GR PRE + POST (1×)	PRE metribuzin + chlorimuron; POST glyphosate (1×)
GR POST	POST glyphosate (2×)
GR PRE + POST (2×)	PRE metribuzin + chlorimuron; POST glyphosate (2×)
Non-GR PRE + POST (grass)	PRE metribuzin + chlorimuron; POST sethoxydim
Non-GR POST	POST bentazon + acifluorfen followed by (fb) clethodim
Non-GR PRE + POST (grass and broadleaf)	PRE metribuzin + chlorimuron; POST sethoxydim fb 2,4-DB + linuron
2000	
GR PRE + POST (1×)	PRE metribuzin + chlorimuron; POST glyphosate (1×)
GR POST	POST glyphosate (2×)
GR PRE + POST (2×)	PRE metribuzin + chlorimuron; POST glyphosate (2×)
Non-GR PRE + POST (grass)	PRE metribuzin + chlorimuron; POST sethoxydim
Non-GR POST	POST bentazon + acifluorfen fb sethoxydim
Non-GR PRE + POST (grass and broadleaf)	PRE metribuzin + chlorimuron; POST sethoxydim fb bentazon + acifluorfen

† 1× or 2× indicates either one or two applications of glyphosate, respectively.

‡ + indicates either a premix or a tank mix.

§ Rates of herbicides (g a.i. ha⁻¹) were metribuzin, 450; chlorimuron, 75; glyphosate, 840; sethoxydim, 213; bentazon, 560; acifluorfen, 280; clethodim, 105; 2,4-DB, 224; and linuron, 560.

plied in 187 L ha⁻¹ water, whereas POST grass herbicides and glyphosate were applied in 94 L ha⁻¹ water. To prevent physical drift to adjacent plots, herbicides were applied using a canopied sprayer (Ginn et al., 1998a) for over-the-top applications or a directed sprayer (Ginn et al., 1998b) for applications underneath the developing soybean canopy. Herbicides and application rates were premix of metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one] at 450 g a.i. ha⁻¹ plus chlorimuron ethyl [ethyl 2-[[[4-(chloro-6-methoxypyrimidin-2-yl)amino]carbonyl]amino]sulfonate] benzoate at 75 g a.i. ha⁻¹ applied PRE; premix of 560 g a.i. ha⁻¹ bentazon [3-(isopropyl)-1H-2,1,3-benzothiadiazin-4-(3H)-one 2,2-dioxide] and 280 g a.i. ha⁻¹ acifluorfen [sodium 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate] applied POST; sethoxydim [2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one] at 213 g a.i. ha⁻¹ applied POST; clethodim [(E)-2-[1-[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one] at 105 g a.i. ha⁻¹ applied POST; glyphosate at 840 g a.i. ha⁻¹ applied POST; and a tank mix of 2,4-DB [4-(2,4-dichlorophenoxy)butyric acid, dimethylamine salt] at 224 g a.i. ha⁻¹ plus linuron [3-(3, 4-dichlorophenyl)-1-methoxy-1-methylurea] at 560 g a.i. ha⁻¹ applied POST as a directed spray underneath the soybean canopy.

Irrigation was started each year at or near beginning bloom and was continued until the full seed stage. Irrigation water was applied by the furrow method through gated rollout vinyl pipe whenever soil water potential at the 30-cm depth, as measured by tensiometers, decreased to about -50 kPa. Irrigation amounts were dictated by the degree of cracking in this shrink-swell soil (cracks when dry, swells when wet) since water applied to it through surface irrigation flows downward to the depth of cracking and rises to the surface as the cracks fill (Mitchell and van Genuchten, 1993). Irrigation starting and ending dates, and total irrigation water applied each year, respectively, were 16 June, 6 August, and 320 mm in 1999 and 14 June, 14 August, and 340 mm in 2000.

Total weed cover was determined (Elmore and Heatherly, 1988) after soybean leaf senescence (just before harvest) each year to measure the season-long effect of the WMSs. Weed cover by species was estimated visually from five randomly chosen 0.5-m² sample areas in each plot. Estimates of weed cover in 10% increments from 0 to 100% were made to estimate cover for each weed species. If a species was present in any of the samples of an individual plot, then its relative abundance was categorized as at least 0 to 10% (average of 5% cover) in that sample. This is similar to the process used by Yelverton and Coble (1991) to measure weed resurgence at the end of the growing season following early-season application of WMSs intended to give 100% control.

Just before harvest each year, mature plant height (length from the soil surface to the tip of stem) was measured in all plots. Lodging ratings were recorded each year, but none exceeded a score of 1 (almost all plants erect). Thus, lodging data are not presented. A field combine modified for small plots was used to harvest all plots on 10 Sept. 1999 and 14 Sept. 2000. Seed from all plots were cleaned by the harvesting machine; thus, correction for foreign matter content in seed of any treatment combination was not necessary in any year. Harvested seed were weighed and adjusted to 130 g moisture kg⁻¹ seed.

Estimates of total expenses and returns were developed for each annual cycle of each experimental unit using the Mississippi State Budget Generator (Spurlock and Laughlin, 1992). Total specified expenses were calculated using actual inputs for each treatment in each year of the experiment and included all operating expenses and machinery ownership

costs, but excluded charges for land, management, and general farm overhead, which were assumed to be the same for all treatment combinations. Machinery ownership costs for tractors, self-propelled harvesters, implements, sprayers, and the irrigation system were estimated by computing the annual capital recovery charge for each machine and applying its per-hectare rate to each field operation. Operating expenses included those for: herbicides and adjuvants, seed, rollout vinyl pipe used in irrigation, and labor; fuel, repair, and maintenance of machinery and irrigation system; hauling harvested seed; and interest on operating capital. Weed management expenses after planting were calculated for each treatment and included charges for herbicides, surfactants, and application. All application charges included both operating expenses and ownership costs associated with tractors and sprayers. Costs for machinery and operating expenses were based on prices paid by Mississippi farmers each year. Irrigation expenses were based on a 65-ha furrow irrigation setup and included an annualized cost for the engine, well, pump, gearhead, and land leveling.

The USDA loan rate of \$0.20 kg⁻¹ seed for Mississippi was used to calculate income from each experimental unit each year. Net return above total specified expenses was determined for each experimental unit each year. Analysis of variance [PROC MIXED (SAS Inst., 1996)] was used to evaluate the significance of WMS and WMS × tillage treatment effects on weed cover, plant height, seed yield, and net return. Analyses across years treated year as a fixed effect to determine interactions involving year. Analyses for individual years treated WMS as a fixed effect. Mean separation was achieved with an LSD_{0.05}.

RESULTS AND DISCUSSION

Weather

Thirty-year average monthly maximum air temperatures and total rainfall (Boykin et al., 1995) at Stoneville are presented in Table 1. In 1999 and 2000, average monthly maximum air temperatures generally were near normal from April through June (Table 1). In 1999, April-through-June rain was slightly above normal while April-through-June rainfall in 2000 was greater than normal. Both cultivars were setting pods during the late May through late June period of each year; therefore, their vegetative and early reproductive periods (before irrigation initiation in mid-June) had favorable weather in both years. In both years, average monthly maximum air temperatures in July and August were slightly or greatly above normal, and July and August rainfall was substantially below normal.

Weed Management Expense and Total Expense

Weed management costs for GR and non-GR cultivars were always less with POST-only than with PRE + POST weed management (Table 3). The 2-yr average weed management costs for POST weed management were \$75 and \$73 ha⁻¹ for GR (includes greater seed cost) and non-GR cultivars, respectively. The highest average weed management expenses of \$129 and \$130 ha⁻¹ for GR (includes greater seed cost of \$23 ha⁻¹ in 1999 and \$21 ha⁻¹ in 2000) and non-GR cultivars, respectively, were incurred for PRE + POST weed management where POST applications were timed to con-

Table 3. After-planting weed management expense and total expense (excluding charges for land, management, and general farm overhead) for weed management systems (WMS) using pre-emergent (PRE) and postemergent (POST) herbicides applied to irrigated glyphosate-resistant (GR) and non-GR soybean grown following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, 1999–2000.

WMS†	Weed expense‡	Total expense		
		DT	ST	DT – ST§
		\$ ha ⁻¹		
<u>1999</u>				
GR PRE + POST (1×)	104	463	430	33
GR POST	78	435	394	41
GR PRE + POST (2×)	135	495	463	32
Non-GR PRE + POST (grass)	85	447	415	32
Non-GR POST	74	435	403	32
Non-GR PRE + POST (grass and broadleaf)	129	495	460	35
<u>2000</u>				
GR PRE + POST (1×)	93	488	448	40
GR POST	72	468	428	40
GR PRE + POST (2×)	123	520	480	40
Non-GR PRE + POST (grass)	83	484	444	40
Non-GR POST	71	471	430	41
Non-GR PRE + POST (grass and broadleaf)	130	535	494	41
<u>1999–2000 average</u>				
GR PRE + POST (1×)	98	476	439	37
GR POST	75	452	411	41
GR PRE + POST (2×)	129	508	472	36
Non-GR PRE + POST (grass)	84	466	430	36
Non-GR POST	73	453	416	37
Non-GR PRE + POST (grass and broadleaf)	130	515	477	38

† 1× and 2× indicate one or two applications of glyphosate, respectively.

‡ Includes extra seed cost of \$23 ha⁻¹ in 1999 and \$21 ha⁻¹ in 2000 for GR cultivars.

§ DT minus ST represents expense differences between DT and ST tillage systems.

tol both grass and broadleaf weeds. Total estimated expenses from using DT were always greater (Table 3). Total expenses associated with using GR and non-GR cultivars were similar because the greater cost for seed of GR cultivars was offset by the cheaper glyphosate.

Plant Height and Weed Cover

Across-years analyses revealed significant interactions involving year and fall tillage and/or WMS for both plant height and weed cover. Therefore, individual-year results are shown. In all WMSs, plants grown following DT were 5 to 29 cm taller than those following ST, and weed cover in DT was always less than that in ST. Increased plant height of soybean grown dryland following fall DT compared with ST at this location has been measured (Heatherly and Spurlock, 2001). Evidently, the DT treatment resulted in a more favorable soil water environment for early-season growth before irrigation initiation than did the ST treatment in this irrigated study, and this aided in the suppression of weeds in DT compared with ST. This is supported by results reported by Wesley and Smith (1991).

Weed management system was erratic in its effect on soybean height. In 1999, fall tillage treatment significantly interacted with WMS to affect height. In ST, height of soybean plants in POST-only weed management was greater than that of plants in PRE + POST

Table 4. Plant height of and weed cover in irrigated glyphosate-resistant (GR) and non-GR soybean grown under weed management systems (WMS) using pre-emergent (PRE) and postemergent (POST) applications of herbicides in plantings following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, in 1999. The fall tillage × WMS interaction was significant; therefore, mean separation among WMSs is shown separately for each fall tillage treatment.

WMS†	Plant height		Weed cover	
	ST	DT	ST	DT
cm				
%				
GR PRE + POST (1×)	72bc‡	93a	38ab	6a
GR POST	79a	96a	15cd	5a
GR PRE + POST (2×)	68c	97a	48a	10a
Non-GR PRE + POST (grass)	66c	85b	19cd	11a
Non-GR POST	76ab	87b	29bc	7a
Non-GR PRE + POST (grass + broadleaf)	66c	88b	10d	1a

† 1× and 2× indicate one or two applications of glyphosate, respectively. For herbicides and their rates, see Table 2.

‡ Values in individual columns within a year that are followed by the same letter are not significantly different at $p \leq 0.05$.

weed management (Table 4). In DT, height of plants was not affected by PRE + POST vs. POST-only weed control. In 2000, plants of the GR cultivar were taller when only POST herbicide applications were made regardless of tillage treatment, whereas the opposite occurred with the non-GR cultivar (Table 5). Thus, use of PRE metribuzin + chlorimuron was associated with shorter plants in most cases. This finding corroborates that of Heatherly et al. (2003). Fall DT overcame this effect in 1999.

Intended near-complete control of weeds in all WMSs up to beginning of irrigation was accomplished in all years (data not shown). In 1999, fall tillage treatment significantly interacted with WMS to affect weed cover at soybean maturity. In ST, weed cover in the GR cultivar was less in the POST-only weed management treatment, whereas the opposite was true in the non-GR cultivar (Table 4). In DT, all WMSs resulted in statistically equal weed cover at maturity. In 2000, there was no clear-cut trend in WMS effect on weed cover; however, the most intensive WMS (PRE + POST timed for both grass and broadleaf control) resulted in the lowest

Table 5. Plant height of and weed cover in irrigated glyphosate-resistant (GR) and non-GR soybean grown under weed management systems (WMS) using pre-emergent (PRE) and postemergent (POST) applications of herbicides in plantings following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, in 2000. The fall tillage × WMS interaction was not significant; therefore, mean separation among WMSs is shown for the average of DT and ST values.

WMS†	Plant height	Weed cover
	cm	%
GR PRE + POST (1×)	76c‡	14a
GR POST	85b	4b
GR PRE + POST (2×)	76c	2b
Non-GR PRE + POST (grass)	91a	9ab
Non-GR POST	82b	14a
Non-GR PRE + POST (grass + broadleaf)	90a	3b

† 1× and 2× indicate one or two applications of glyphosate, respectively. For herbicides and their rates, see Table 2.

‡ Values in individual columns that are followed by the same letter are not significantly different at $p \leq 0.05$.

Table 6. Major weed species† present in irrigated glyphosate-resistant (GR) and non-GR soybean grown under weed management systems (WMS) using pre-emergent (PRE) and postemergent (POST) applications of herbicides in plantings following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, 1999–2000.

WMS‡	ST, DT§				
	Browntop millet	Pitted morningglory	Redvine	Ivyleaf morningglory	Johnsongrass
	%				
	1999				
GR PRE + POST (1×)	32, 0	2, 0	0, 3		
GR POST	8, 0	3, 0	3, 3		
GR PRE + POST (2×)	37, 6	2, 0	5, 3		
Non-GR PRE + POST (grass)	7, 0	3, 0	6, 8		
Non-GR POST	3, 0	12, 4	11, 0		
Non-GR PRE + POST (grass + broadleaf)	7, 0		3, 0		
	2000				
GR PRE + POST (1×)	14, 0	8, 0	3, 2		
GR POST			6, 0		
GR PRE + POST (2×)			4, 0		
Non-GR PRE + POST (grass)			10, 2	0, 2	
Non-GR POST			15, 0		4, 4
Non-GR PRE + POST (grass + broadleaf)			3, 0		

† Browntop millet, *Brachiaria ramosa* (L.) Stapf; ivyleaf morningglory, *Ipomoea hederacea* (L.) Jacq.; johnsongrass, *Sorghum halepense* (L.) Pers.; pitted morningglory, *Ipomoea lacunosa* L.; redvine, *Brunnichia ovata* (Walt.) Shinnars.

‡ For herbicides and their rates, see Table 2.

§ First number of a pair is percentage cover in ST; second number is percentage cover in DT.

numerical weed cover values in GR and non-GR cultivars (Table 5). The greatest weed cover at soybean maturity generally occurred in the WMSs with the shortest soybean plants. Thus, soybean height and dense soybean canopy in the DT environment acted to suppress late-season weed flushes and overcome the possible deleterious effect of a PRE herbicide.

Predominant weed species in each WMS in ST and DT are shown in Table 6. In treatment combinations that had >10% weed cover (Tables 4 and 5), browntop millet [*Brachiaria ramosa* (L.) Stapf; annual grass], redvine (perennial vine), and pitted morningglory (*Ipomoea lacunosa* L.; annual broadleaf) dominated. Johnsongrass, a dominant perennial grass in the region, appeared only sporadically and in low densities (Table 6). The increased presence of annual grasses (e.g., browntop millet), perennial vines (e.g., redvine), and johnsongrass was predicted by Koskinen and McWhorter (1986) for reduced-till systems used in soybean production. However, the 2-yr duration of our study was not long enough to verify increases in these weeds.

Seed Yield and Net Return

Analyses revealed that effect of fall tillage and WMS were consistent across the 2 yr for both soybean yield

and net return. Therefore, results are reported as the average of 1999 and 2000 data (Table 7). Tillage system did not significantly interact with WMS to affect seed yield in this irrigated environment. Average yields from DT and ST across 1999 and 2000 were 4286 and 4084 kg ha⁻¹. This 202 kg ha⁻¹ average yield difference translates to \$40 ha⁻¹ greater average income from DT (using \$0.20 kg⁻¹ seed), which is barely greater than the \$38 ha⁻¹ greater average expense associated with DT (Table 3). Thus, average net returns of \$364 ha⁻¹ and \$362 ha⁻¹ from DT and ST, respectively, are nearly identical. Weed management system significantly affected yield. The non-GR cultivar outyielded the GR cultivar regardless of weed management (4484, 4450, and 4512 kg ha⁻¹ compared with 3777, 4078, and 3812 kg ha⁻¹, respectively). This agrees with results from irrigated studies conducted by Webster et al. (1999) in Arkansas and Heatherly et al. (2003) in Mississippi. The significant interaction resulted because the 4078 kg ha⁻¹ yield from the POST-only weed management of the GR cultivar was significantly greater than the 3777 and 3812 kg ha⁻¹ yields from the PRE + POST weed management treatments, respectively, while the non-GR cultivar yields from all weed management treatments were not different. Therefore, POST-only weed management for

Table 7. Seed yield and net return from irrigated glyphosate-resistant (GR) and non-GR soybean grown under weed management systems (WMS) using pre-emergent (PRE) and postemergent (POST) applications of herbicides in plantings following shallow (ST) and deep (DT) fall tillage at Stoneville, MS. Data are averaged for 1999 and 2000.

WMS†	Seed yield			Net return		
	ST	DT	Mean	ST	DT	Mean
	kg ha ⁻¹			\$ ha ⁻¹		
GR PRE + POST (1×)	3669	3885	3777c‡	282	288	285c
GR POST	4095	4060	4078b	394	347	370b
GR PRE + POST (2×)	3728	3897	3812c	261	258	260c
Non-GR PRE + POST (grass)	4364	4604	4484a	429	439	434a
Non-GR POST	4317	4582	4450a	432	448	440a
Non-GR PRE + POST (grass + broadleaf)	4335	4688	4512a	375	407	391b

† 1× and 2× indicate one or two applications of glyphosate, respectively. For herbicides and their rates, see Table 2.

‡ Average values in individual columns that are followed by the same letter are not significantly different at $p \leq 0.05$. The fall tillage × WMS interaction was not significant for either seed yield or net return, but ST and DT values are given to show magnitude of values for each fall tillage treatment.

GR cultivars resulted in the greatest yield while use of PRE + POST or POST-only weed management with non-GR cultivars made no difference in yield.

Average net returns to ST and DT were \$362 and \$364 ha⁻¹, respectively (Table 7). Weed management system significantly affected net return. Net returns from the non-GR cultivar exceeded those from the GR cultivar (\$434, \$440, and \$391 ha⁻¹ compared with \$285, \$370, and \$260 ha⁻¹, respectively), but the difference between GR and non-GR cultivars was smaller when POST-only weed management was used. Average net return from POST-only weed management exceeded that from weed management treatments that used PRE + POST weed management (\$370 ha⁻¹ vs. \$285 and \$260 ha⁻¹) when the GR cultivar was used. When the non-GR cultivar was used, POST-only net return exceeded that from PRE + POST weed management when both grass and broadleaf POST herbicides were used. Consequently, total POST weed management strategies with both GR and non-GR cultivars provided the combination of the most profit with the least expense.

CONCLUSIONS

Results from this 2-yr study lead to several conclusions. Taller soybean plants and less weed cover at harvest were associated with DT compared with ST. Thus, DT in the fall provided an environment that fostered increased growth during the soybean vegetative period, and this increased growth resulted in reduced weed pressure once soybean had matured. The long-term effect of taller plants in an irrigated DT environment on changes in annual grasses and perennial vines as predicted by Koskinen and McWhorter (1986) cannot be surmised from these short-term results.

The increased expense associated with use of PRE broadleaf and POST herbicides timed for both grass and broadleaf control resulted in less weed cover at soybean maturity in some cases but did not translate to increased yields or profits. In an ST system on this soil, use of POST-only glyphosate with the GR cultivar resulted in less weed cover than did the use of a weed management treatment with a PRE component. With non-GR cultivars, the opposite was true. In a DT system on this soil, choice of weed management was not important for weed control in either GR or non-GR cultivars. Differences in yield and net return between DT and ST were not significant in this irrigated environment on clay soil.

Once a producer has purchased a DT implement, the decision to deep-till in a given year depends only on whether or not the potential revenue gain will be greater than the additional operating cost—not the additional total cost. The only relevant cost to consider when making such a short-term decision is the operating cost. On the other hand, a producer who has not purchased an implement and a large tractor necessary for DT should consider returns above total costs before making the purchase; that is, the long-term decision should be to purchase the implement and large tractor only if both

operation and ownership costs can be covered by the additional revenue. In this study, we have computed returns above total costs. Thus, producers who already own a DT implement and large tractor (and are evaluating the short-term decision of whether or not to DT) should attempt to estimate the likely returns above their own operating costs. If equipment for DT is not on hand, the low response of irrigated soybean to DT of Sharkey clay in this study indicates that over the long term, DT may not be justified. These results do not support the investment required to obtain the necessary equipment to deep-till soils that will be cropped to irrigated soybean.

Fall DT of Sharkey soil often results in soft soil that will not support equipment in the spring. This soft soil can delay planting past the intended early to mid-April dates. This should be considered in relation to the high yield expected from early planted, irrigated ESPS soybean and the potential for lost yield if planting is delayed (Heatherly, 1999a, 1999b). If the normal two fall tillage operations (disk harrow followed by disk harrow or field cultivator) used in ST in these studies are replaced by no-till systems, the resulting cost savings of \$17 to \$25 ha⁻¹ will provide even more impetus to exclude DT from consideration.

Yield levels in this irrigated study were quite high (3570 to 4690 kg ha⁻¹), response to DT was relatively low, and nonirrigated yields in the region are low (Heatherly, 1999a). This leads to the conclusion that any increased investment for soybean production in the midsouthern USA should go toward enhancing irrigation capability where adequate water is available rather than increasing DT capability since the return on irrigation is much greater.

ACKNOWLEDGMENTS

The authors appreciate the technical assistance provided by Lawrence Ginn, Sandra Mosley, and John Black; resources provided by the Delta Research and Extension Center; and supplemental funding provided by the Mississippi Soybean Promotion Board.

REFERENCES

- Boykin, D.L., R.R. Carle, C.D. Ranney, and R. Shanklin. 1995. Weather data summary for 1964–1993, Stoneville, MS. Tech. Bull. 201. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.
- Buhler, D.D., R.P. King, S.M. Swinton, J.L. Gunsolus, and F. Forcella. 1997. Field evaluation of a bioeconomic model for weed management in soybean (*Glycine max*). Weed Sci. 45:158–165.
- Camp, C.R., and E.J. Sadler. 2002. Irrigation, deep tillage, and nitrogen management for a corn-soybean rotation. Trans. ASAE 45: 601–608.
- Corrigan, K.A., and R.G. Harvey. 2000. Glyphosate with and without residual herbicides in no-till glyphosate-resistant soybean (*Glycine max*). Weed Technol. 14:569–577.
- Elmore, C.D., and L.G. Heatherly. 1988. Planting system and weed control effects on soybean grown on clay soil. Agron. J. 80:818–821.
- Elmore, R.W., F.W. Roeth, R. Klein, S.Z. Knezevic, A. Martin, L. Nelson, and C.A. Shapiro. 2001. Glyphosate-resistant soybean cultivar response to glyphosate. Agron. J. 93:404–407.
- Frederick, J.R., P.J. Bauer, W.J. Busscher, and G.S. McCutcheon. 1998. Tillage management for doublecropped soybean grown in narrow and wide row width culture. Crop Sci. 38:755–762.
- Frederick, J.R., C.R. Camp, and P.J. Bauer. 2001. Drought-stress

- effects on branch and mainstem seed yield and yield components of determinate soybean. *Crop Sci.* 41:759–763.
- Ginn, L.H., E.R. Adams, L.G. Heatherly, and R.A. Wesley. 1998a. A canopied sprayer for accurate application of herbicides. *Agron. J.* 90:109–112.
- Ginn, L.H., L.G. Heatherly, E.R. Adams, and R.A. Wesley. 1998b. A sprayer for under-canopy application of herbicide sprays. *J. Prod. Agric.* 11:196–199.
- Gonzini, L.C., S.E. Hart, and L.M. Wax. 1999. Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). *Weed Technol.* 13:354–360.
- Heatherly, L.G. 1981. Soybean response to tillage of a Sharkey clay soil. *Bull.* 892. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.
- Heatherly, L.G. 1999a. Early soybean production system (ESPS). p. 103–118. *In* L.G. Heatherly and H.F. Hodges (ed.) *Soybean production in the Mid-south*. CRC Press, Boca Raton, FL.
- Heatherly, L.G. 1999b. Soybean irrigation. p. 119–142. *In* L.G. Heatherly and H.F. Hodges (ed.) *Soybean production in the Mid-south*. CRC Press, Boca Raton, FL.
- Heatherly, L.G. 1999c. The stale seedbed planting system. p. 93–102. *In* L.G. Heatherly and H.F. Hodges (ed.) *Soybean production in the Mid-south*. CRC Press, Boca Raton, FL.
- Heatherly, L.G., C.D. Elmore, and S.R. Spurlock. 1994. Effect of irrigation and weed control treatment on yield and net return from soybean (*Glycine max*). *Weed Technol.* 8:69–76.
- Heatherly, L.G., and S.R. Spurlock. 1999. Yield and economics of traditional and early soybean production system (ESPS) seedlings in the midsouthern United States. *Field Crops Res.* 63:35–45.
- Heatherly, L.G., and S.R. Spurlock. 2001. Economics of fall tillage for early and conventional plantings of soybean in the midsouthern USA. *Agron. J.* 93:511–516.
- Heatherly, L.G., S.R. Spurlock, J. Black, and R.A. Wesley. 2002. Fall tillage for soybean grown on Delta clay soils. *Bull.* 1117. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.
- Heatherly, L.G., S.R. Spurlock, and C.D. Elmore. 2003. Weed management systems for conventional and glyphosate-resistant soybean following rice. *Bull.* 1135. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.
- Heatherly, L.G., R.A. Wesley, C.D. Elmore, and S.R. Spurlock. 1993. Net returns from stale seedbed plantings of soybean (*Glycine max*) on clay soil. *Weed Technol.* 7:972–980.
- Hoelt, R.G., E.D. Nafziger, R.R. Johnson, and S.R. Aldrich. 2000. *Modern corn and soybean production*. 1st ed. MCSP Publ., Champaign, IL.
- Johnson, W.G., J.A. Kendig, R.E. Massey, M.S. DeFelice, and C.D. Becker. 1997. Weed control and economic returns with postemergence herbicides in narrow-row soybeans. *Weed Technol.* 11:453–459.
- Koskinen, W.C., and C.G. McWhorter. 1986. Weed control in conservation tillage. *J. Soil Water Conserv.* 41:365–370.
- Mitchell, A.R., and M.Th. van Genuchten. 1993. Flood irrigation of a cracked soil. *Soil Sci. Soc. Am. J.* 57:490–497.
- Nelson, K.A., and K.A. Renner. 1999. Weed management in wide- and narrow-row glyphosate-resistant soybean. *J. Prod. Agric.* 12:460–465.
- Pettry, D.E., and R.E. Switzer. 1996. Sharkey soils in Mississippi. Mississippi Agric. and Forestry Exp. Stn. *Bull.* 1057. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.
- Popp, M.P., T.C. Keisling, C.R. Dillon, and P.M. Manning. 2001. Economic and agronomic assessment of deep tillage in soybean production on Mississippi River Valley soils. *Agron. J.* 93:164–169.
- Poston, D.H., E.C. Murdock, and J.E. Toler. 1992. Cost-efficient weed control in soybean (*Glycine max*) with cultivation and banded herbicide application. *Weed Technol.* 6:990–995.
- Reddy, K.N. 2001a. Weed management in transgenic soybean resistant to glyphosate under conventional tillage and no-tillage systems. *J. New Seeds* 3:27–40.
- Reddy, K.N. 2001b. Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges. *Weed Biol. Manage.* 1:193–202.
- Reddy, K.N., L.G. Heatherly, and A. Blaine. 1999. Weed management. p. 171–195. *In* L.G. Heatherly and H.F. Hodges (ed.) *Soybean production in the Mid-south*. CRC Press, Boca Raton, FL.
- Reddy, K.N., R.E. Hoagland, and R.M. Zablotowicz. 2000. Effect of glyphosate on growth, chlorophyll, and nodulation in glyphosate-resistant and susceptible soybean (*Glycine max*) varieties. *J. New Seeds* 2:37–52.
- Reddy, K.N., and K. Whiting. 2000. Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. *Weed Technol.* 14: 204–211.
- Roberts, R.K., R. Pendergrass, and R.M. Hayes. 1999. Economic analysis of alternative herbicide regimes on Roundup Ready soybeans. *J. Prod. Agric.* 12:449–454.
- SAS Institute. 1996. SAS system for mixed models. SAS Inst, Cary, NC.
- Spurlock, S.R., and D.H. Laughlin. 1992. Mississippi State Budget Generator user's guide. Version 3.0. Agric. Econ. Tech. Publ. 88. Dep. of Agric. Econ., Mississippi State Univ., Mississippi State.
- Webster, E.P., K.J. Bryant, and L.D. Earnest. 1999. Weed control and economics in nontransgenic and glyphosate-resistant soybean (*Glycine max*). *Weed Technol.* 13:586–593.
- Wesley, R.A., and L.A. Smith. 1991. Response of soybean to deep tillage with controlled traffic on clay soil. *Trans. ASAE* 34:113–119.
- Wesley, R.A., L.A. Smith, and S.R. Spurlock. 1994. Fall deep tillage of clay: Agronomic and economic benefits. *Bull.* 1015. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.
- Wesley, R.A., L.A. Smith, and S.R. Spurlock. 2000. Residual effects of fall deep tillage on soybean yields and net returns on Tunica clay soil. *Agron. J.* 92:941–947.
- Wesley, R.A., L.A. Smith, and S.R. Spurlock. 2001. Fall deep tillage of Tunica and Sharkey clay: Residual effects on soybean yield and net return. *Bull.* 1102. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.
- Yelverton, F.H., and H.D. Coble. 1991. Narrow row spacing and canopy formation reduces weed resurgence in soybeans (*Glycine max*). *Weed Technol.* 5:169–174.